Real-Time Orbit Feedback at the APS

J.A. Carwardine and F.R. Lenkszus

Advanced Photon Source, Argonne National Laboratory

Outline

- Overview
- Real-Time Orbit Feedback Implementation
- System performance
- Corrector dynamics & equalization
- Local feedback
- Real-time diagnostics & applications
- Future prospects for orbit stability at the APS
- Closing Remarks

Advanced Photon Source
Storage Ring Design Characteristics

• Energy:	7.0 GeV
• Stored Beam Current (design):	100 mA
• Stored Beam Lifetime (design):	>10 hrs
• Circumference:	1104 m
• Number of Super-periods:	40
• Harmonic Number:	1296
• RF Frequency:	351.93 MHz
• Horizontal Tune:	35.2
• Vertical Tune:	14.3
• Synchrotron Tune:	0.0072
• Horiz. Beam Size at ID Source:	325 μm rms
• Vertical Beam Size at ID Source:	86 μm rms
• X-Y Coupling	10 %
• Straight Sections for I.D.'s:	35

Orbit Feedback System Requirements

APS Orbit Stability Specifications

- Beam must be stable to within 5% of its size.
- Horizontal stability specification: 17μm rms.
- Vertical stability specification: 4.4μm rms.

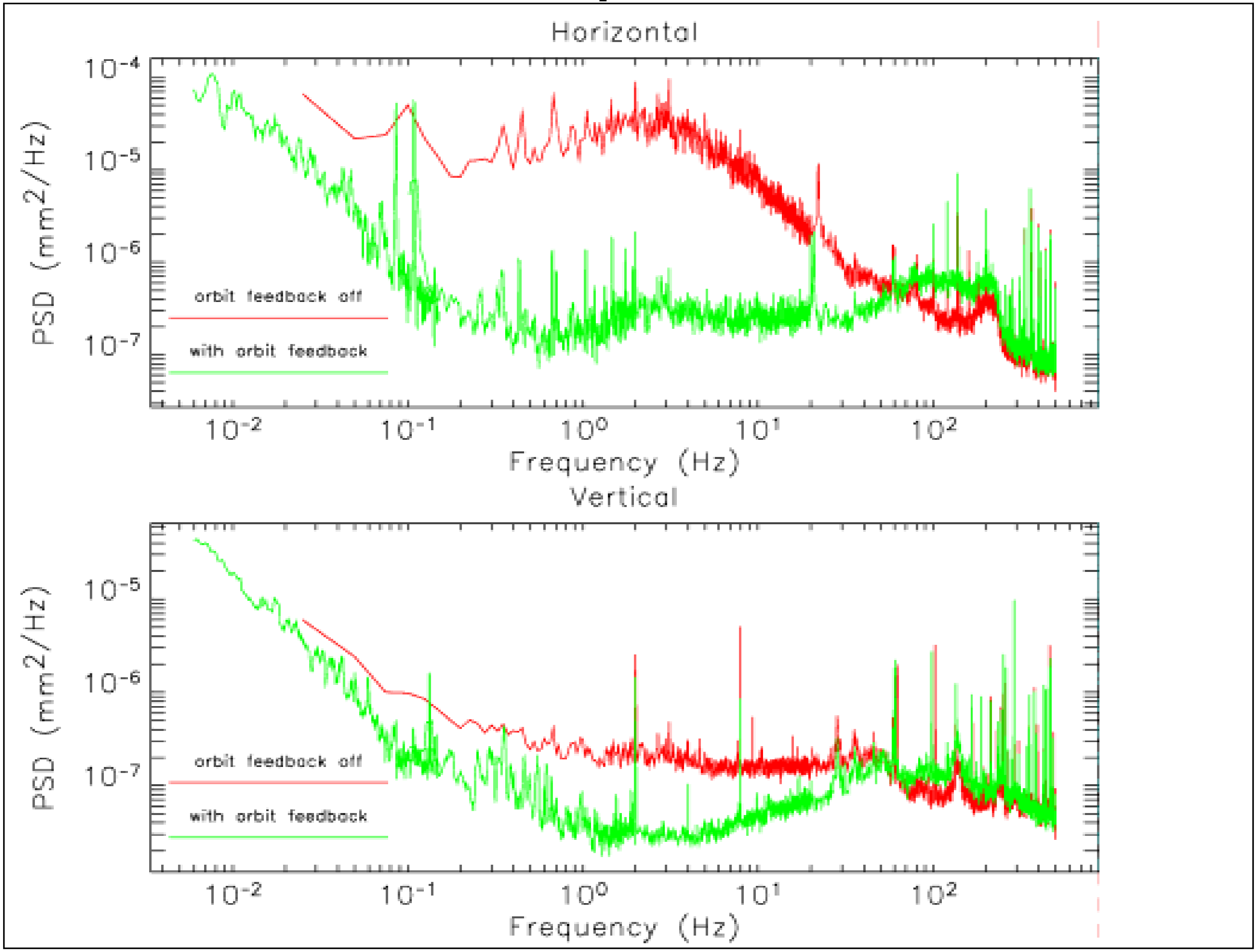
Orbit Feedback System Functionality

- ‘Global’ (long wavelength) feedback to minimize rms orbit errors.
- ‘Local’ feedback to steer the orbit through x-ray source points.

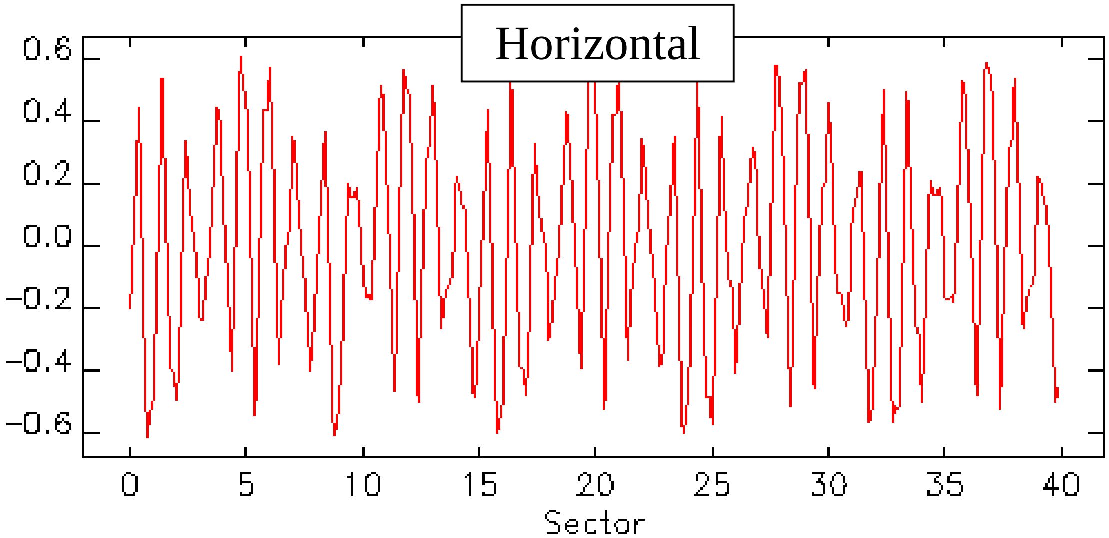
Implementation

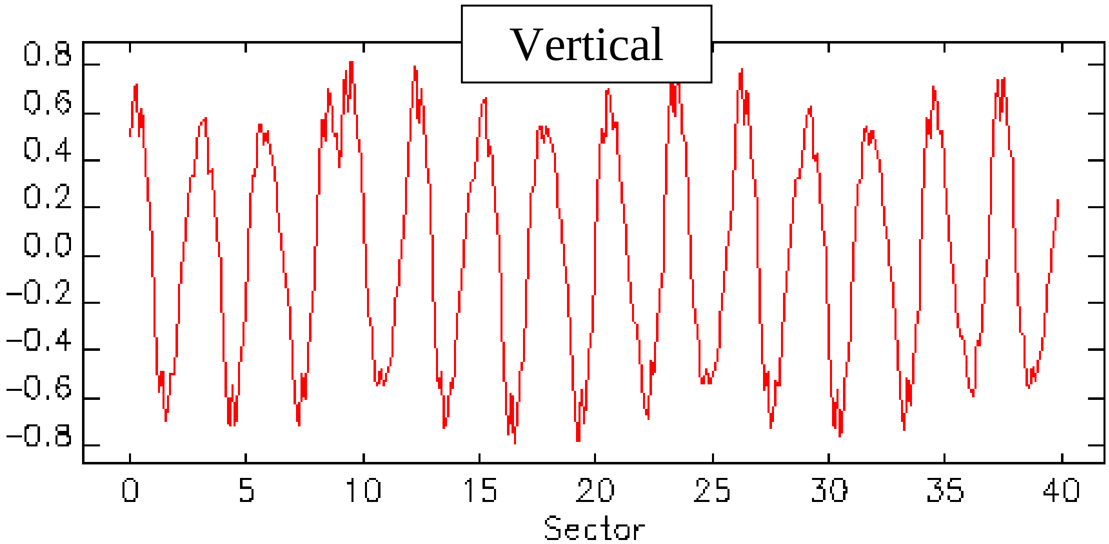
- The system is entirely digital, using DSPs to perform the real-time computations.
- A reflective memory network allows globally-oriented algorithms to be implemented at high rates (1-2kHz).
- Local and global feedback are combined in a single system.
- The global orbit feedback system has been in operation with users since June 1997.

Orbit Motion Power Spectra at ID Source Points



Betatron Orbit Motion





- Orbit disturbances produce an orbit error which follows a closed sinusoidal path relative to the reference orbit.
- This is true both for static disturbances and for dynamic disturbances.
- In the APS, the horizontal betatron tune is 35.2, and the vertical betatron tune is currently 19.3.

The Global Orbit Correction Algorithm

- The global orbit correction algorithm solves a set of linear equations describing the betatron orbit motion:

$$R \cdot \Delta c = \Delta x$$

- The 'inverse response matrix' maps orbit errors at the bpms to changes in corrector strength:

$$R^{-1} \cdot \Delta x = \Delta c$$

- Removal of 'singular values' improves the stability of poorly conditioned inverse response matrices.
- Different bpm & corrector selections will change the outcome.

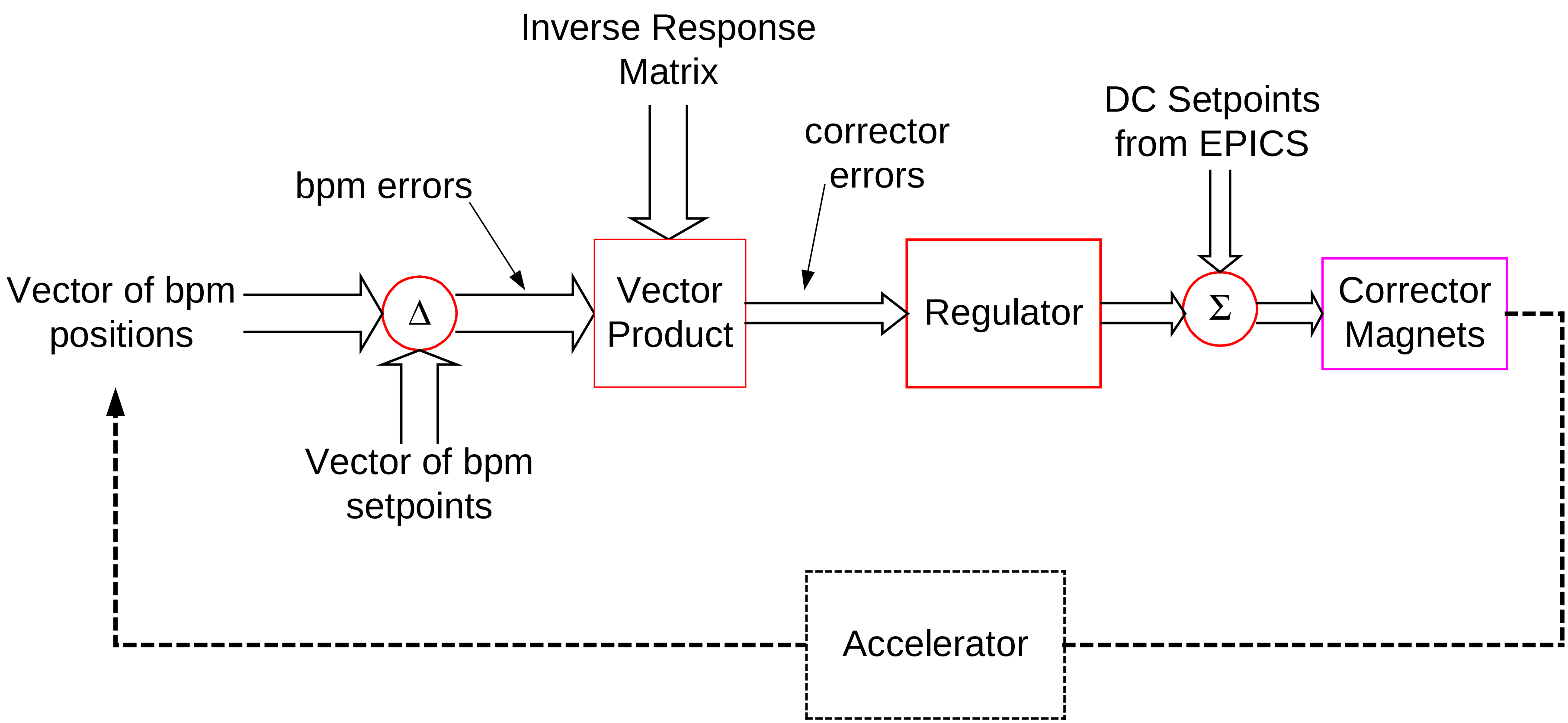
Ex. *Many bpms and few correctors*…

- Least squares minimization of bpm errors.

Ex. Few bpms and many correctors…

- Exact correction at bpm locations.
- Least-squares minimization of corrector power.

The Orbit Feedback Process



Orbit Feedback at APS

‘DC’ Orbit Correction [Emery, PAC 1997]

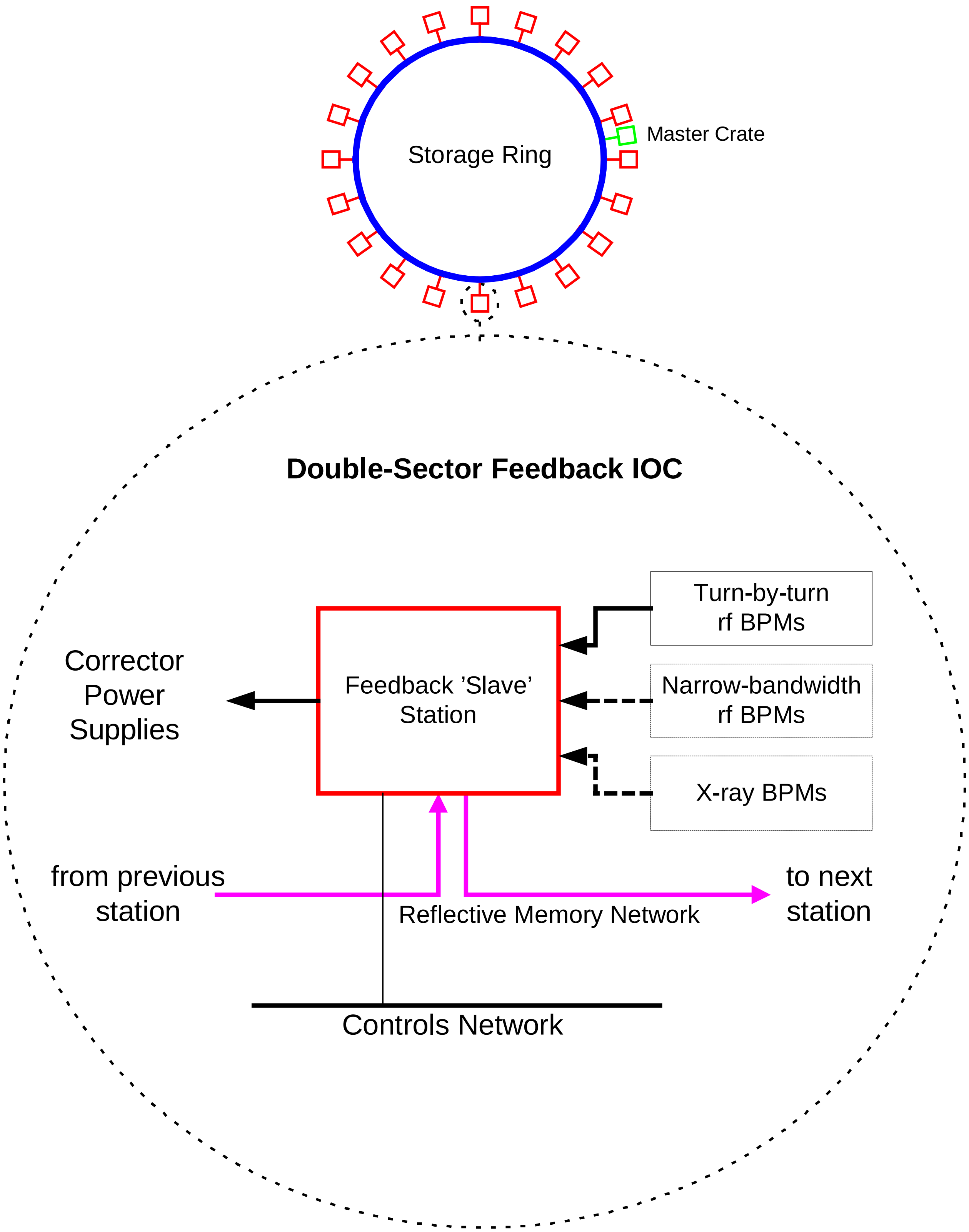
- A workstation-based system corrects the ‘DC’ orbit at 10-second intervals.
- It corrects the global rms orbit using > 300 bpms and 80 correctors.
- No singular values are removed when calculating the inverse response matrix.
- ‘Despiking’ eliminates bpm outliers before calculation of the corrector deltas.
- Bpm offset compensation to reduce beam-current dependences.
- Local steering is implemented on-demand, using a different configuration of bpms and correctors.

Orbit Feedback at APS (cont'd)

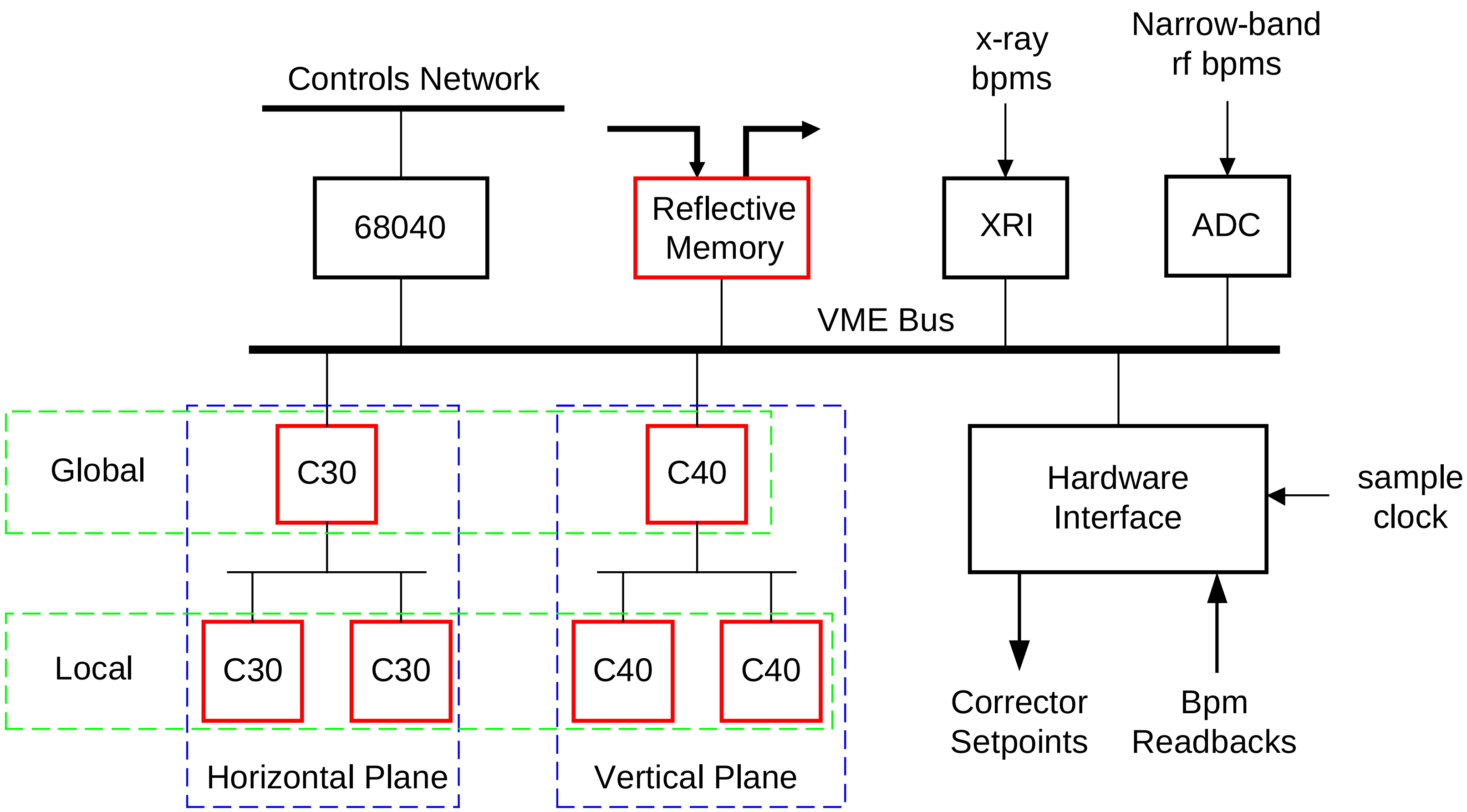
Dynamic Orbit Correction

- The real-time system corrects only dynamic orbit errors at a 1kHz rate (soon to be 2kHz).
- A high-pass filter rolls off the frequency reponse below 20mHz.
- It also corrects the global rms orbit, using 160 bpms and 38 correctors.
- Again, no singular values are removed when calculating the inverse response matrix.
- 'Despiking' is not implemented.

Real-Time Feedback Hardware Scheme



Slave Station Hardware

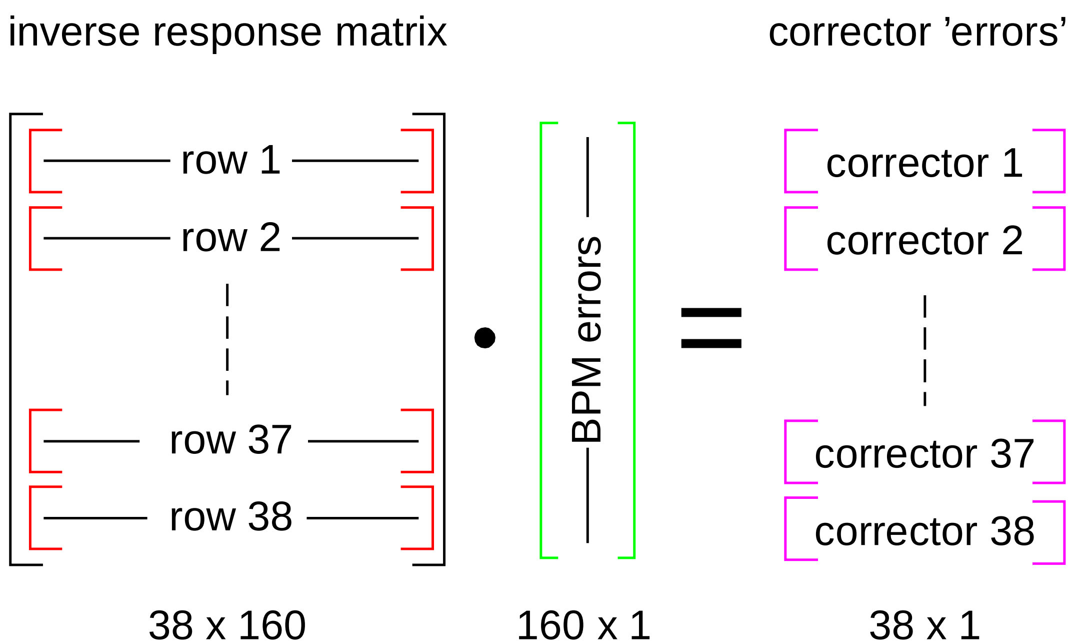


Slave Station Hardware

- The 68040 processor runs EPICS core routines.
- Real-time processing is performed using Texas Instruments TMS320 C30 & C40 floating-point DSPs.
- One C30 DSP has performed global orbit corrections at 1kHz. Adding a C40 DSP has allowed the sampling rate to increase to 2kHz.
- The Reflective Memory network provides station-to-station data transfers at 29.6Mbytes/second.
- X-ray bpms on each beamline and narrow-bandwidth rf bpms at each ID source point will be used for ‘local’ feedback.

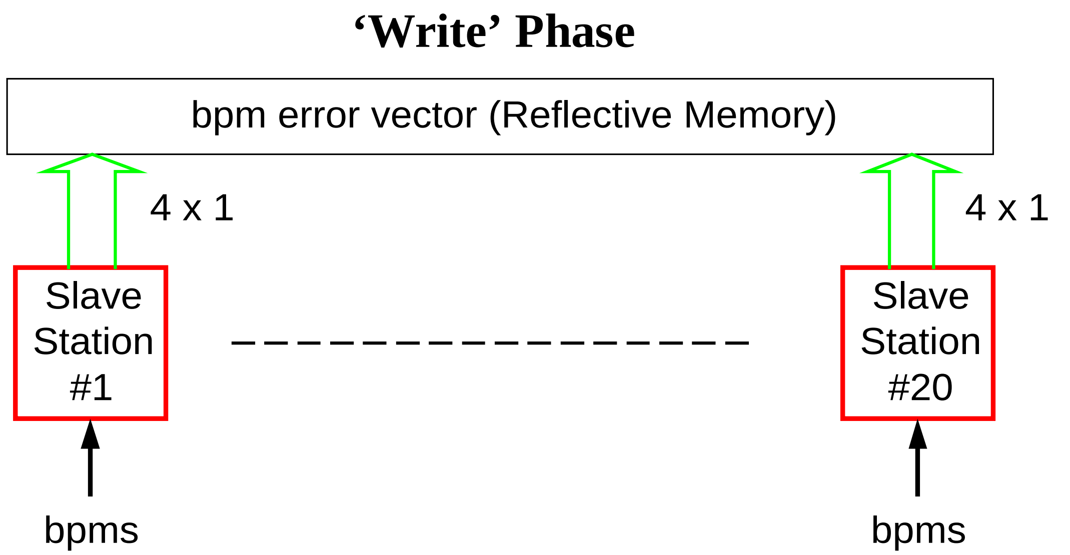
Implementation of the Real-Time Global Orbit Feedback Algorithm

- Computation of corrector 'errors' is conveniently separated into a series of vector dot-products, one for each corrector.

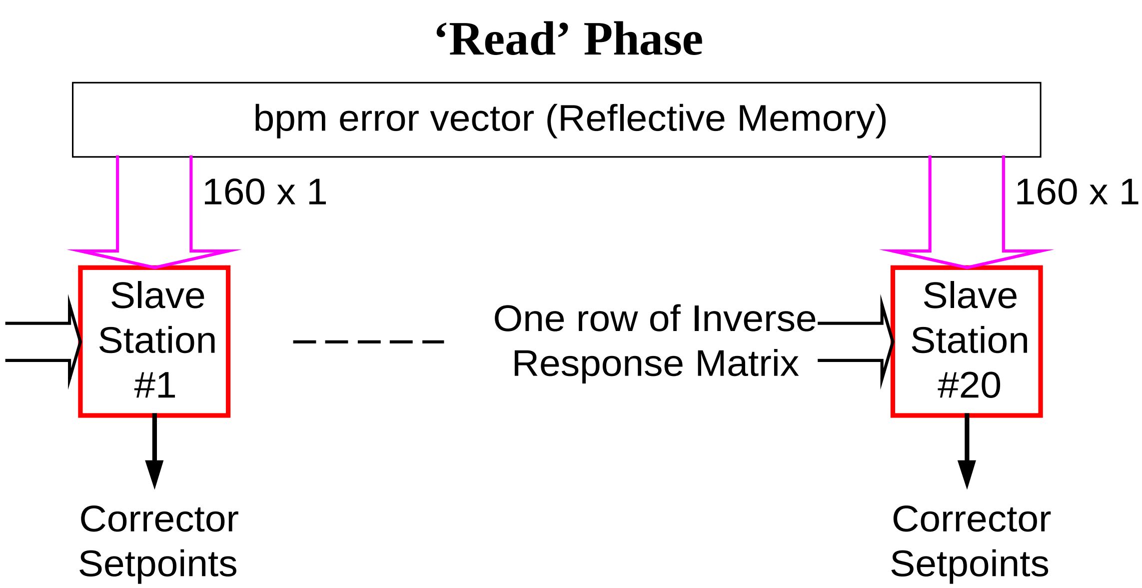


- Each corrector 'error' becomes the input to one of the 38 independent feedback regulators.

The Role of Reflective Memory

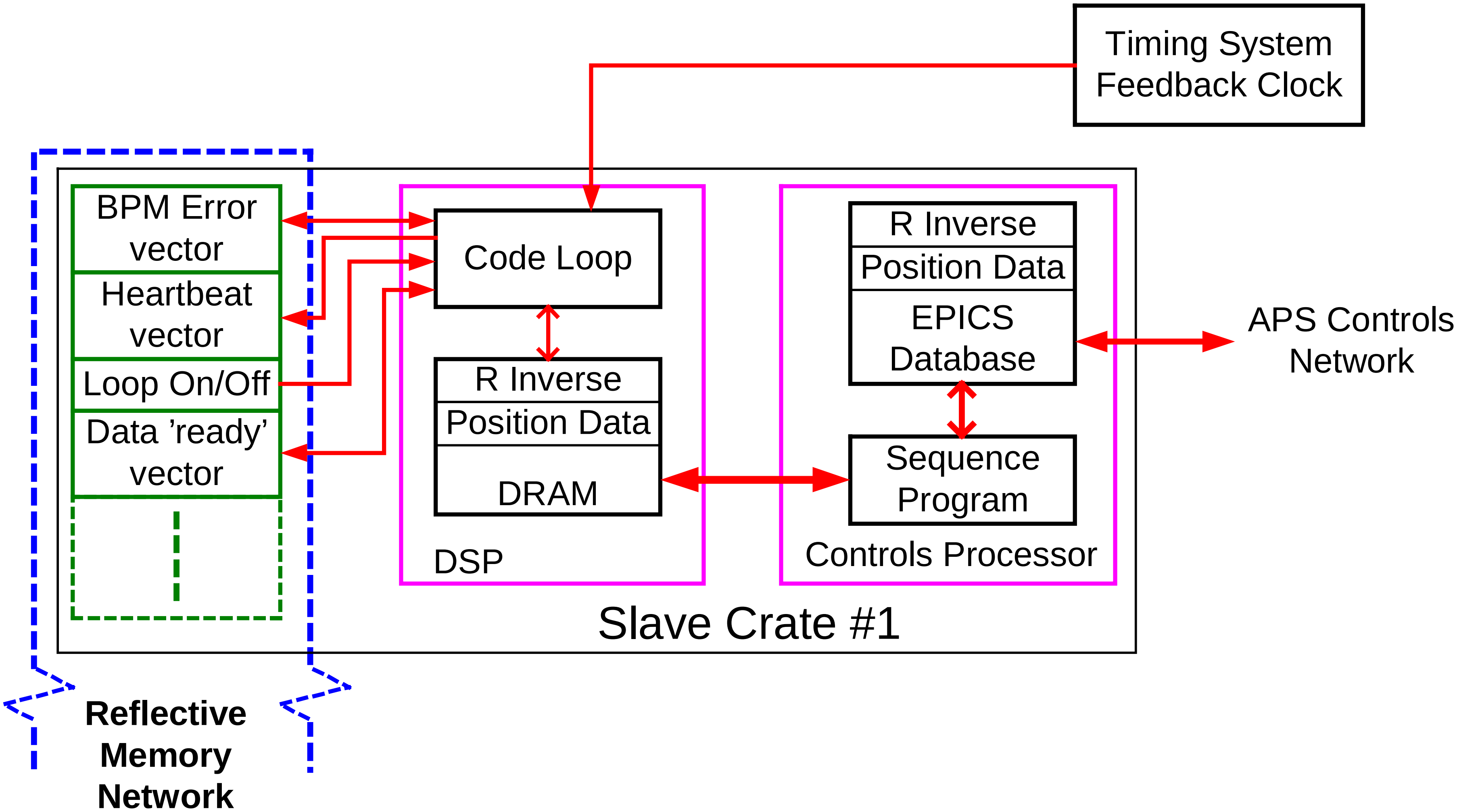


- Bpms directly available to each slave station are written into reflective memory.



- Entire bpm vector is read from reflective memory and used to calculate new corrector setpoints.

Synchronization and Data Sharing

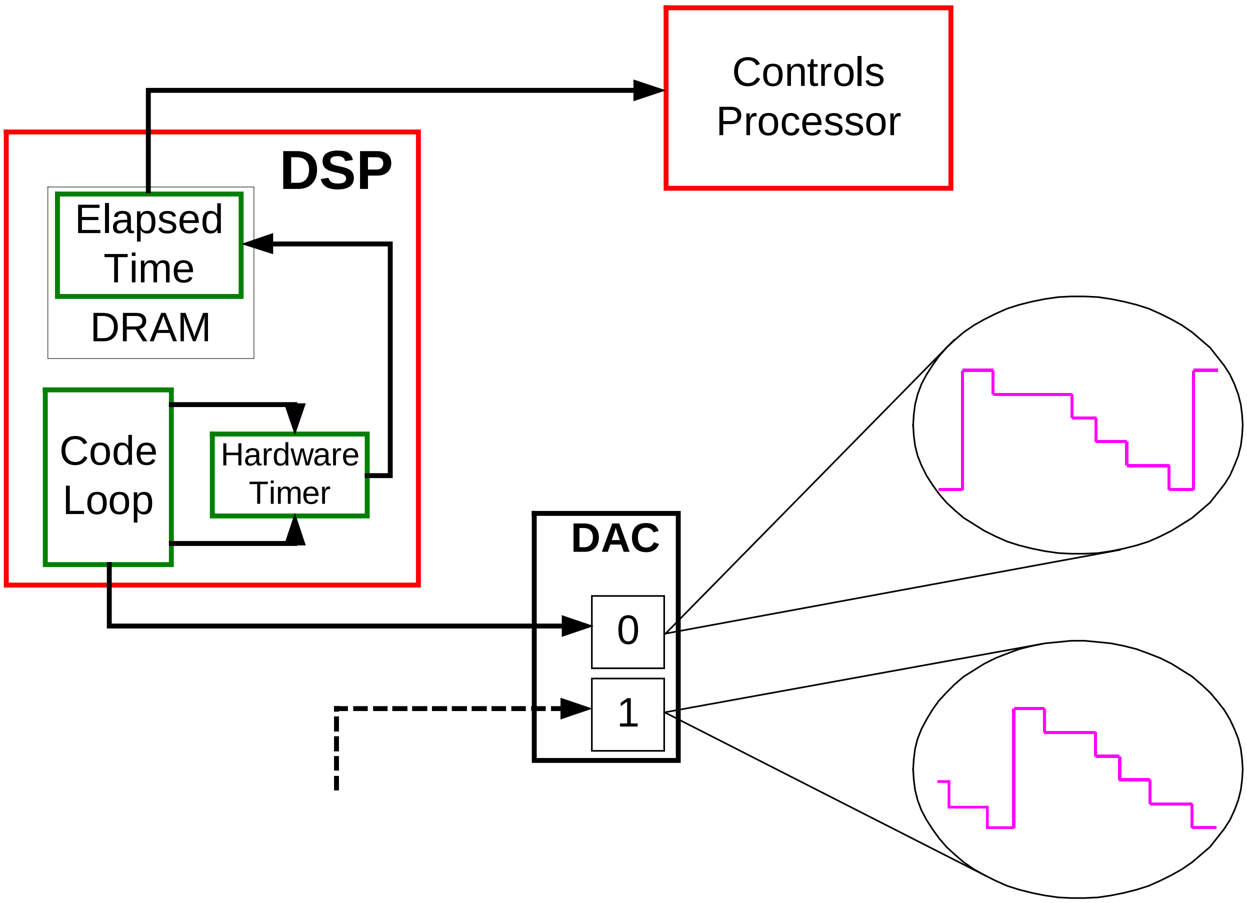


Synchronization

Synchronization

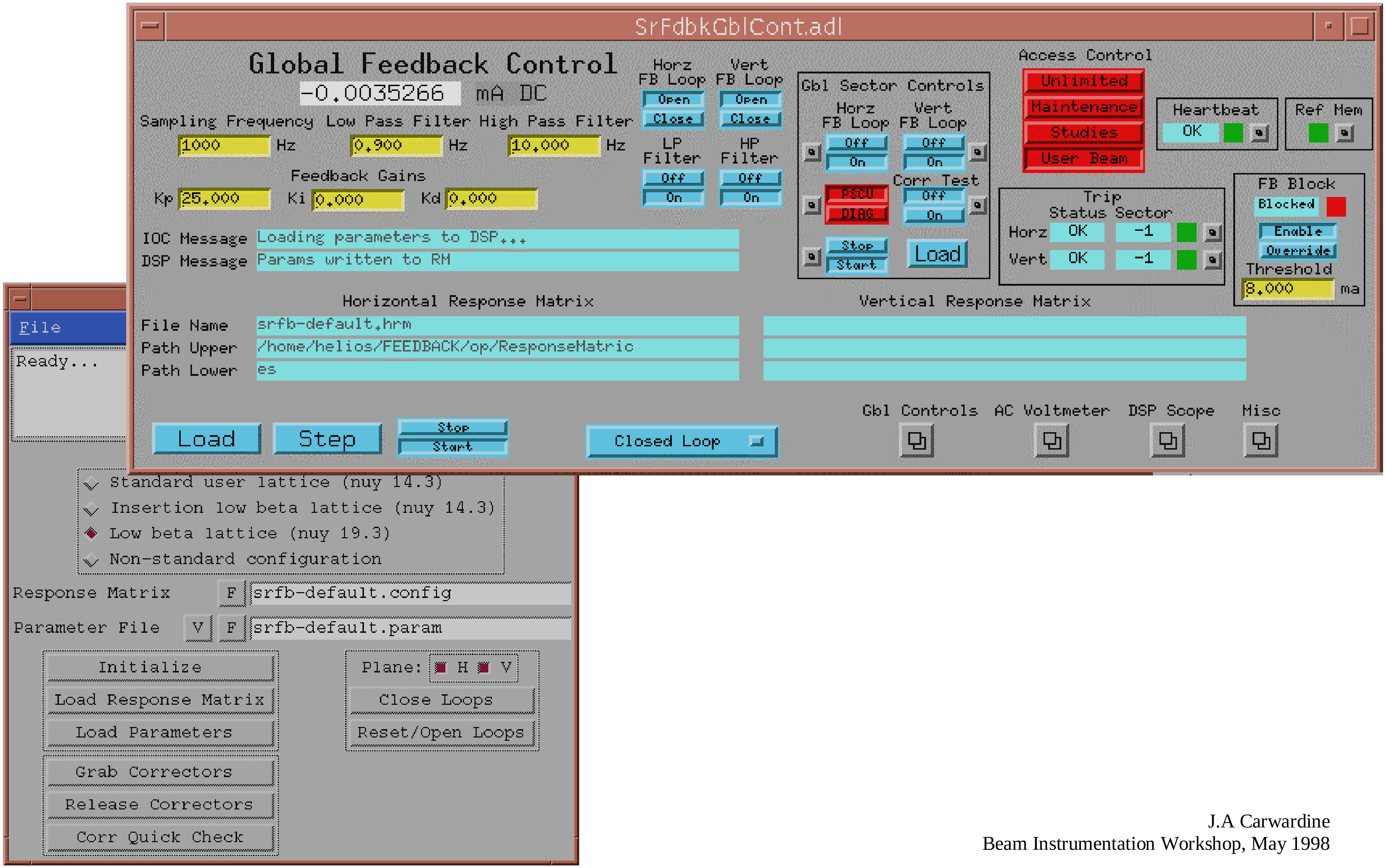
- After computing & writing bpm error values to reflective memory, each DSP sets an assigned word in a ‘data ready’ vector in reflective memory.
- All DSPs “spin-wait” on the ready-vector becoming all ones, before proceeding to read the entire bpm error vector.
- A maximum wait-time prevents complete breakdown if one slave crate fails to write its ready-vector.
- Each slave writes to a heartbeat word in reflective memory that is checked by the master crate.

Timing the DSP Code



- For timing across multiple DSPs, we use a DAC output module. Each DSP writes values to a different channel.
- The DSP's on-board timer chips are used to time sections of code on individual DSPs.

Operator Interface



Operational Issues

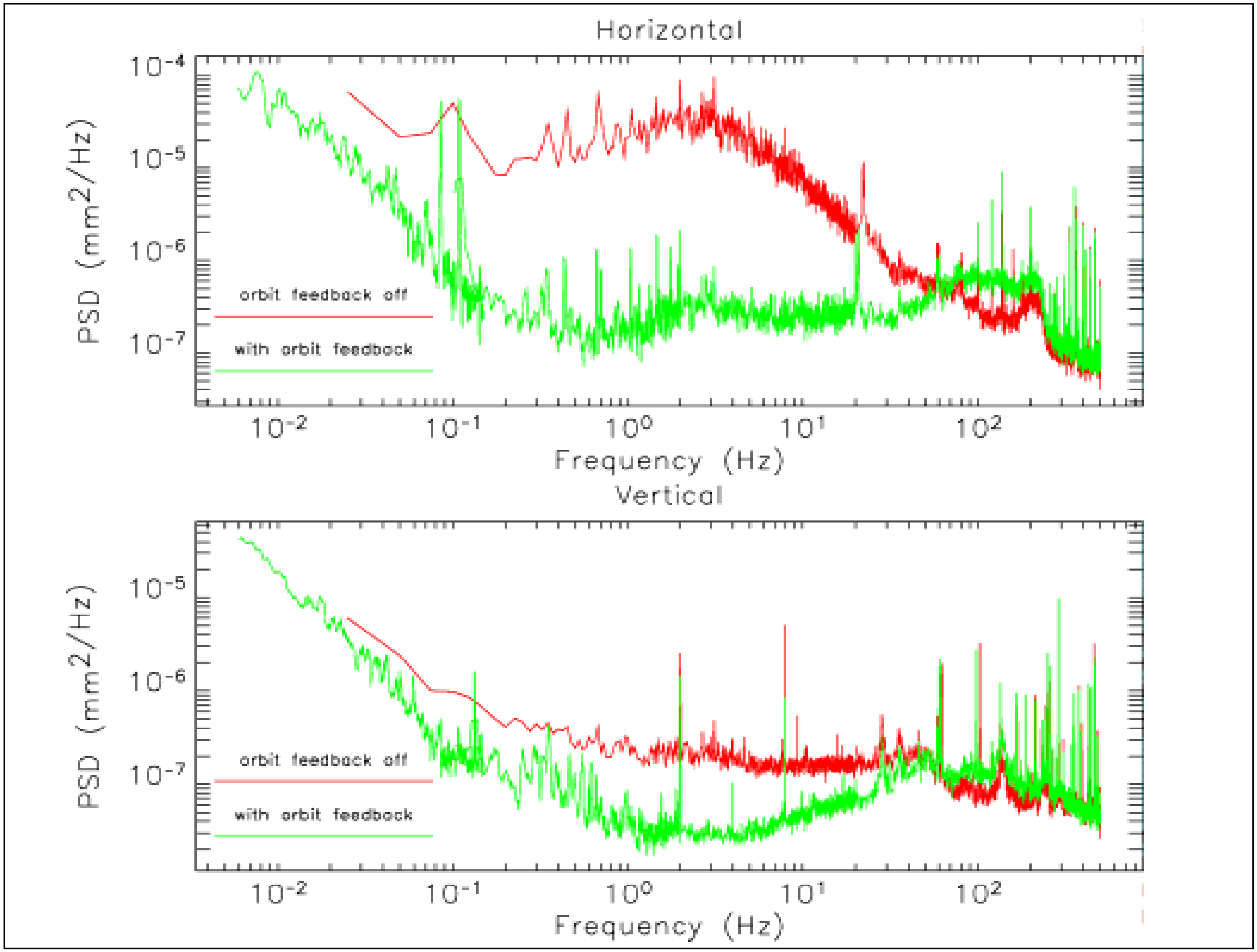
- Orbit feedback control loops can be opened and closed with no impact on stored beam.
- New response matrices can be downloaded to re-configure the system in a few seconds.
- The system turns itself off when beam is lost, and can turn itself back on when beam returns.
- It is not necessary to open the feedback loops during injection.
- In 9 months only one user beam store has been lost due to real-time orbit feedback.
- Since hand-over to operations, the system has been available for > 99% of user beam time.

Orbit Stability at Insertion-Device Source Points

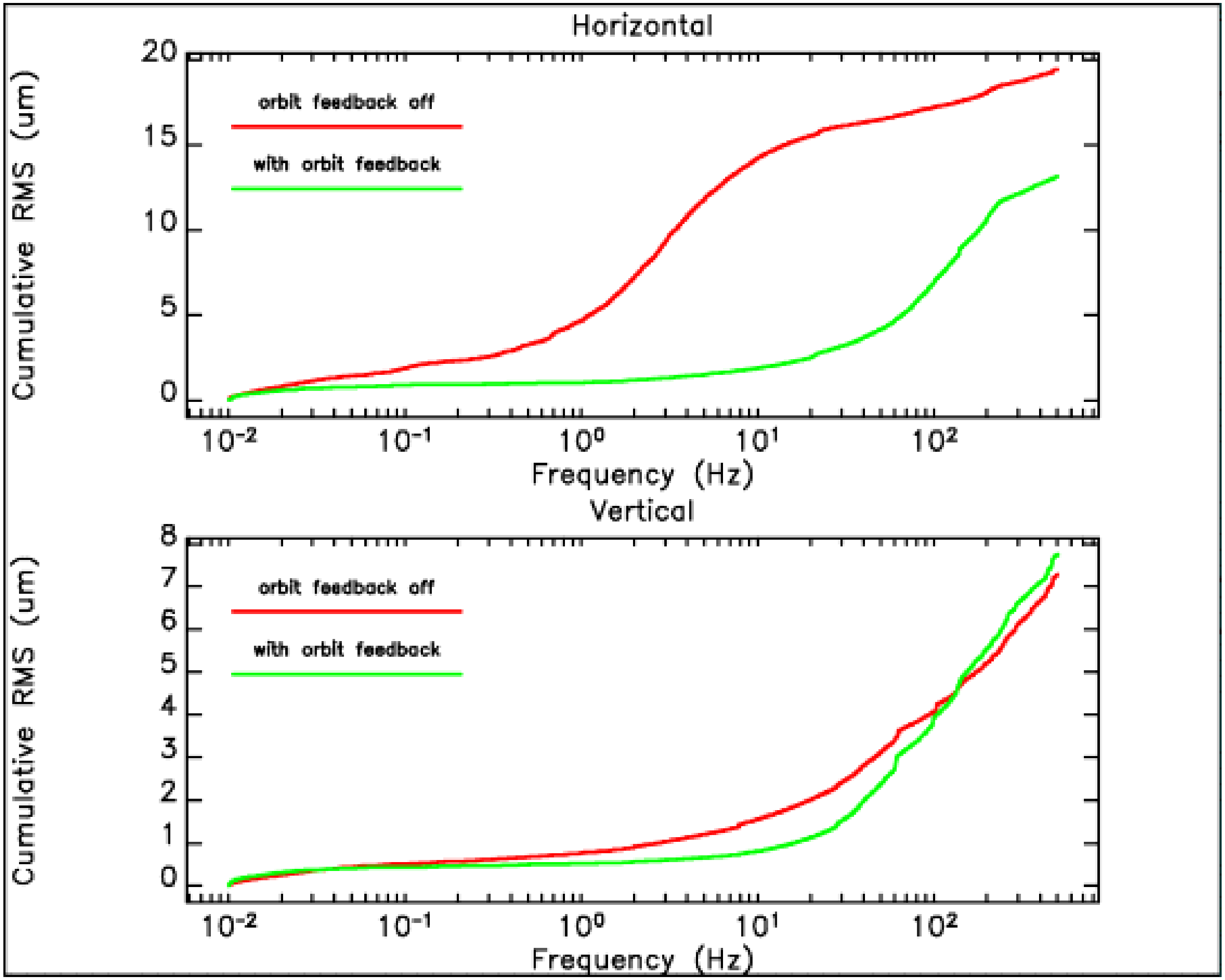
	Horizontal		Vertical	
	No F/B	F/B on	No F/B	F/B on
Required orbit stability (rms) (with 10% x-y coupling)	17.5µm		4.5µm	
Orbit motion 0.016Hz-30Hz (rms)	18.4µm	4.4µm	3.1µm	1.8µm
Orbit motion 0.25Hz-500Hz (rms)	20µm	13.2µm	7.4µm	7.5µm
Beam size at I.D. source points (rms) (inferred from S35BM @ 100mA)	335µm		18µm	
Beta at I.D. source points (design)	17m		3m	

Measurements were taken during the APS "98-2" user run with 1% x-y coupling.

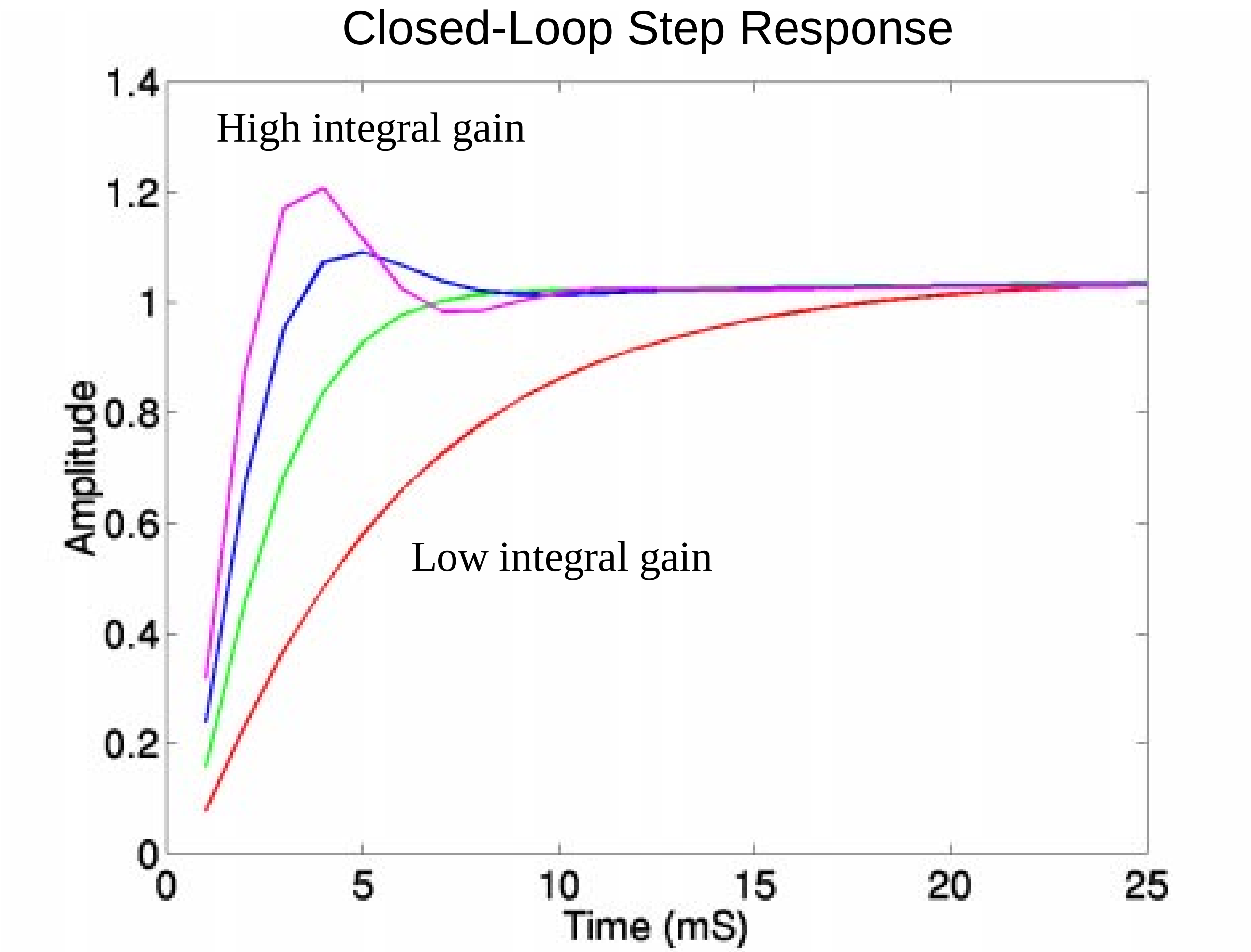
Orbit Motion Power Spectra at ID Source Points



Cumulative RMS Orbit Motion at ID Source Points

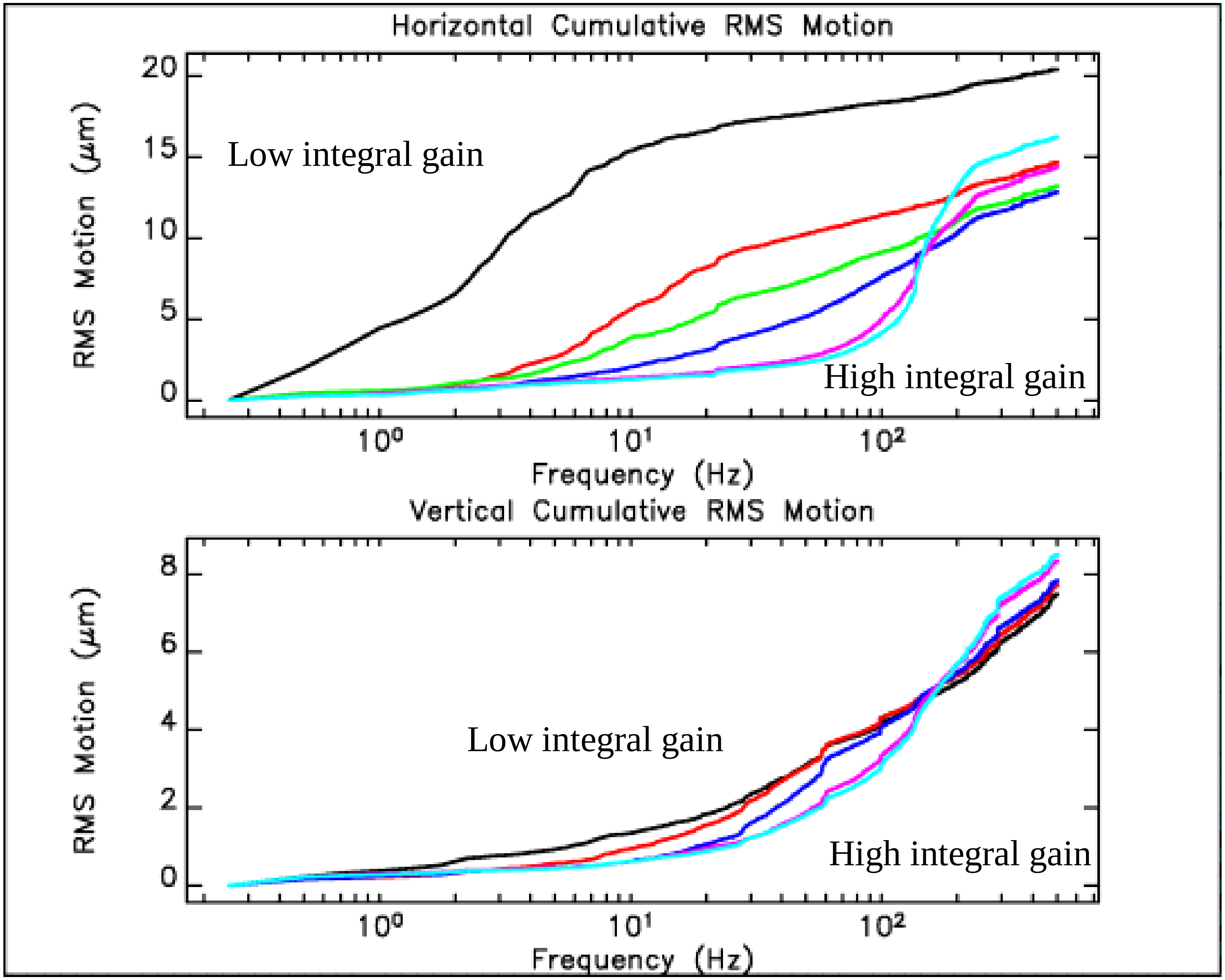


Effect of Regulator Tuning on Closed-Loop Response



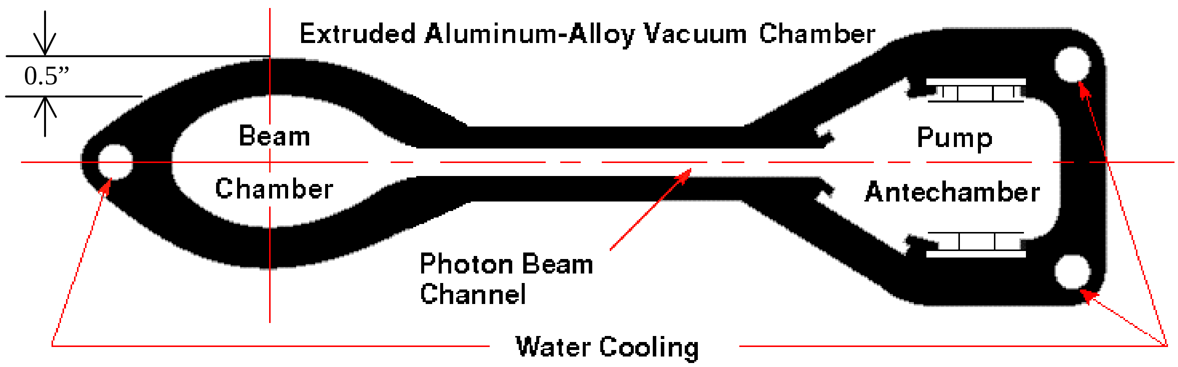
- As the regulator gain is increased, the rise-time is reduced, but the overshoot increases.

Impact of Regulator Tuning on RMS Orbit Stability



Eddy-Current Effects in Corrector Magnet Responses

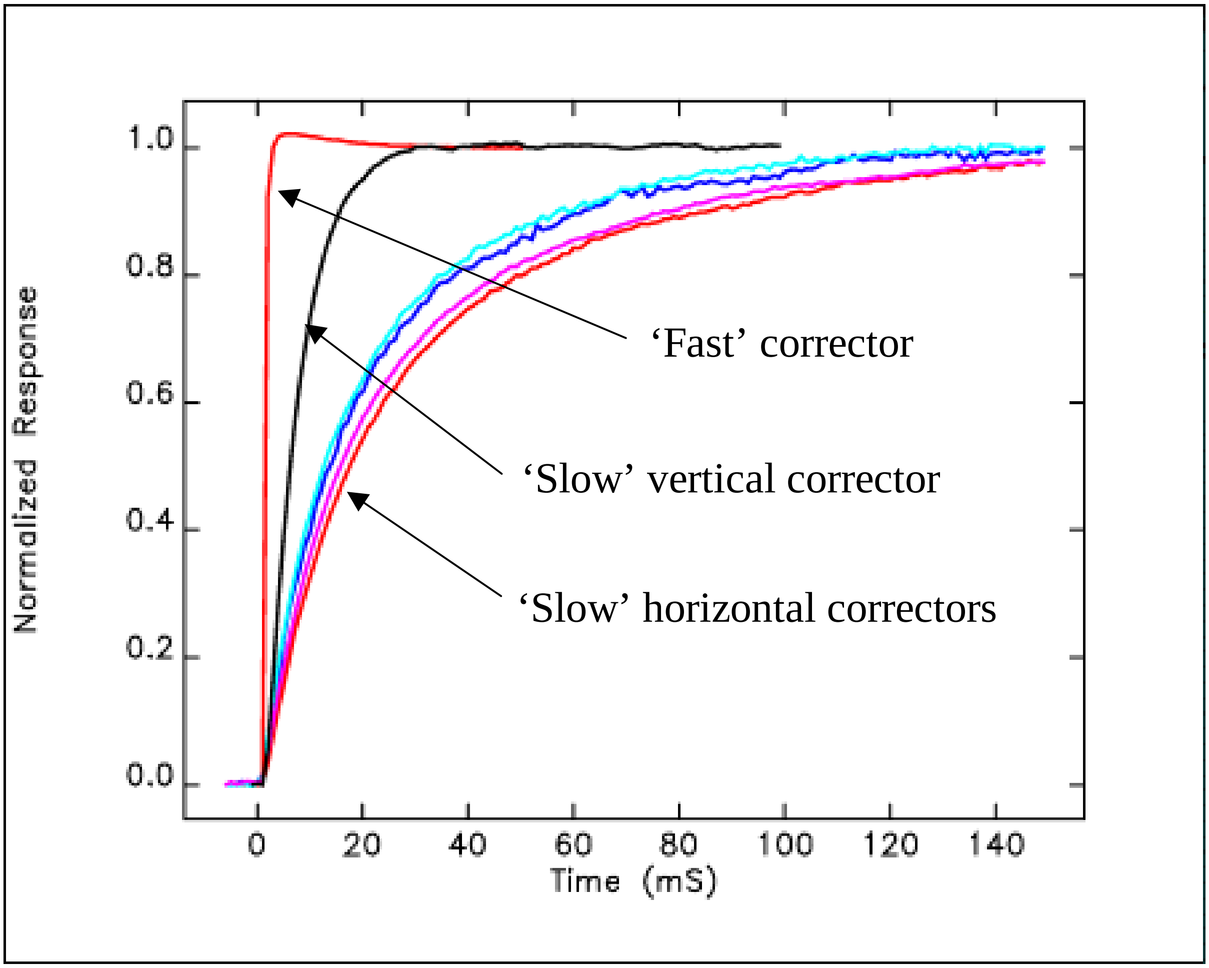
- There are 8 dual-function corrector magnets in each sector of the storage ring.
- All but one of the magnets are subject to eddy-current effects from the aluminum vacuum chamber that significantly slow the dynamic response.



- The one ‘fast’ corrector in each sector is used in the global feedback algorithm since it offers the best correction bandwidth.
- The ‘slow’ correctors will be used to implement local feedback.

Corrector Step Responses

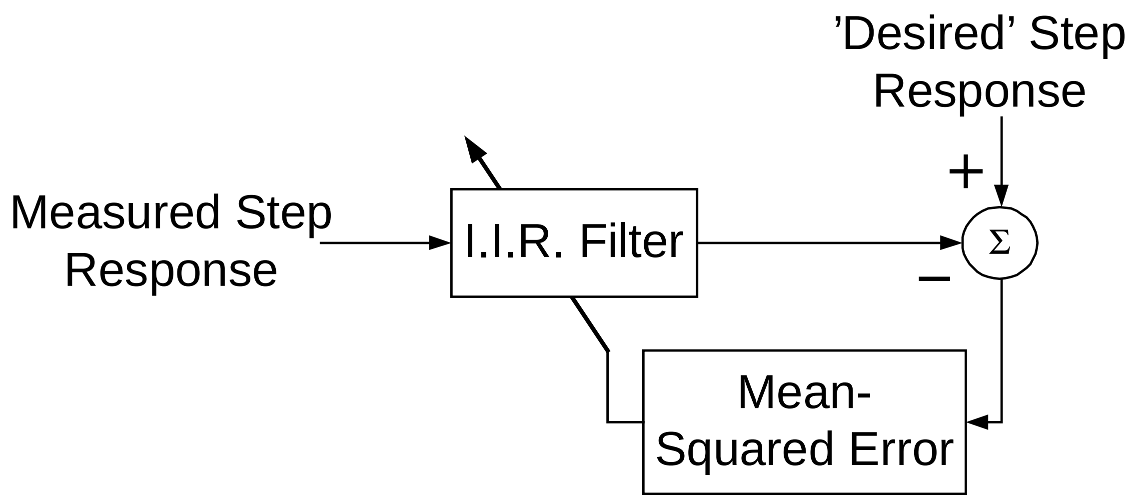
- Corrector 'system' step responses have been measured from the transient response of the global orbit.



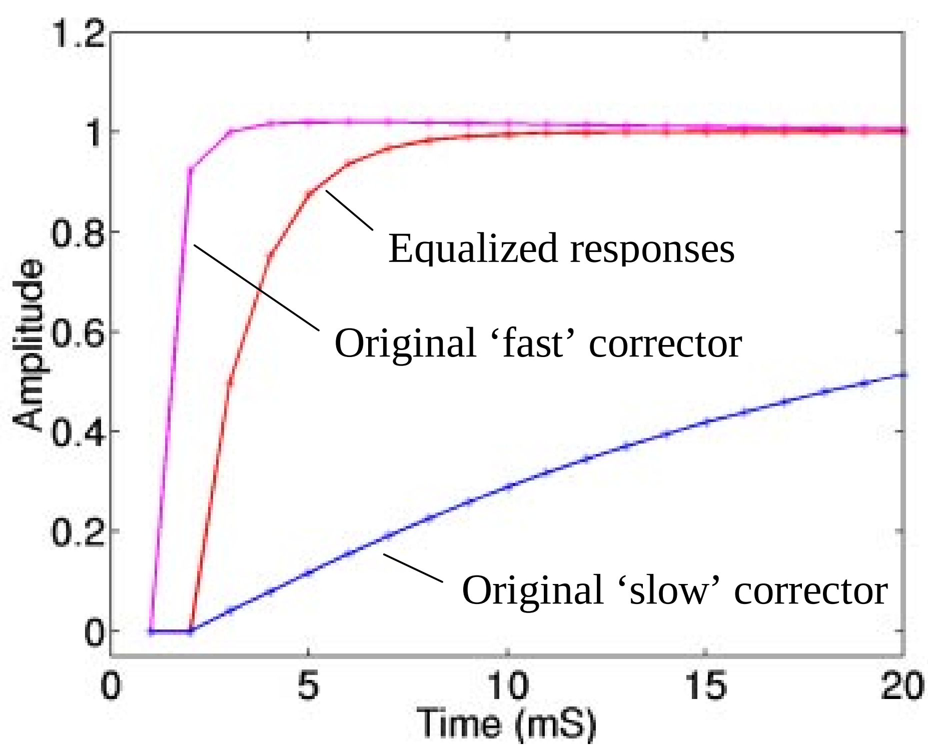
- Significant differences exist between the responses of the horizontal and vertical 'slow' correctors.
- Subtle differences also exist between different slow correctors because of small differences in the mechanical layout of the vacuum chamber.

Step Response Equalization

- Least-squares filter design problem



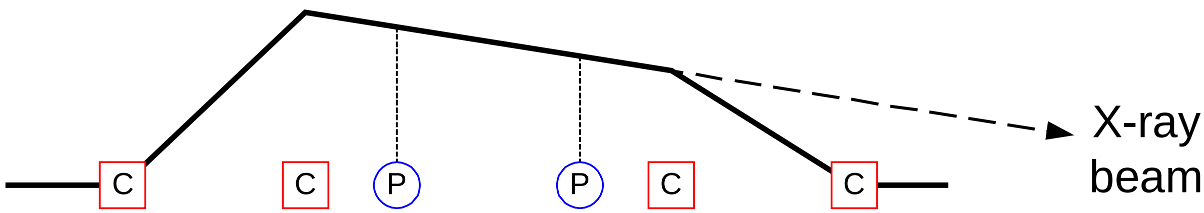
- 'Desired' response was chosen to be a simple low-pass filter with a one-sample delay.
- Resonable results were obtained with a 3-pole, 3-zero IIR filter.



Local Feedback Measurement Issues

- Local feedback requires very stable information about the trajectory of the x-ray beam or of the particle beam through the x-ray source points.
- So far, our position inputs have not been sufficiently stable to support local feedback.
- There are well-known problems with insertion-device photon bpms due to contamination from other x-ray sources.
- We are installing new rf bpm electronics to help improve measurement stability at the insertion-device source points.

Local Feedback: Classic Four-Corrector 'Local Bump'



- Bump 'coefficients' map positions at two bpms to the four corrector strengths.
- Coefficients are computed to ensure that the global orbit is not affected when the bump strength is changed.
- Simple to implement – only requires two bpms.
- Bump coefficients must be well matched to prevent leakage.
- Eddy-current effects make it very difficult for us to get a closed dynamic bump (even with corrector equalization).
- BUT, the same four correctors can be used with bpms outside the bump to help cancel closure errors.

Local Feedback Algorithm Implementation

- A response matrix will be used to implement local feedback at all source-points simultaneously.
- Two options will be evaluated to enable local & global feedback systems to work together.

Frequency-domain separation

- Use local feedback for slower corrections, with global feedback used above a few hertz.
- Does not compromise the overall correction bandwidth.

Combined-Function Response Matrix

- Include both local and global objectives in the same ‘global’ matrix.
- Correction bandwidth will be compromised because the ‘fast’ correctors must be slowed down to match the equalized ‘slow’ correctors.

Real-Time Beam Diagnostics

‘DSPscope’

- Simultaneous collection of 40 channels of time-domain data from bpms, correctors, or regulator error signals.
- Data is provided as EPICS waveforms records.

‘AC Voltmeter’

- Simultaneous sliding Fourier transforms of 40 selectable data channels.
- Simultaneous sliding Fourier transforms of all 320 BPM channels in either plane.

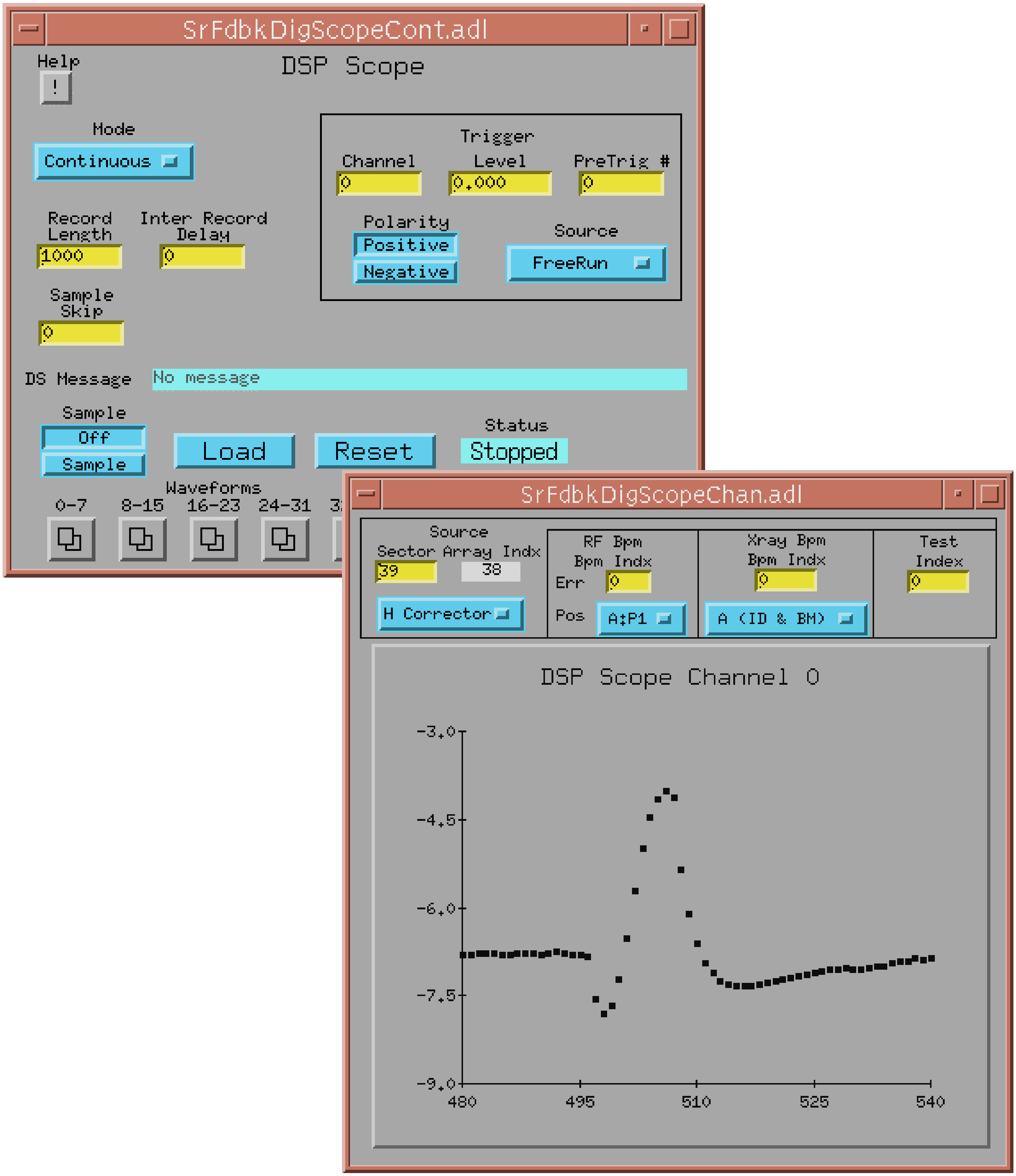
Corrector Error Statistics

- Sliding estimates of the *mean* and *variance* of the corrector errors are computed at each sample tick.
- Used to detect problems with the orbit feedback system itself and to detect BPM problems.

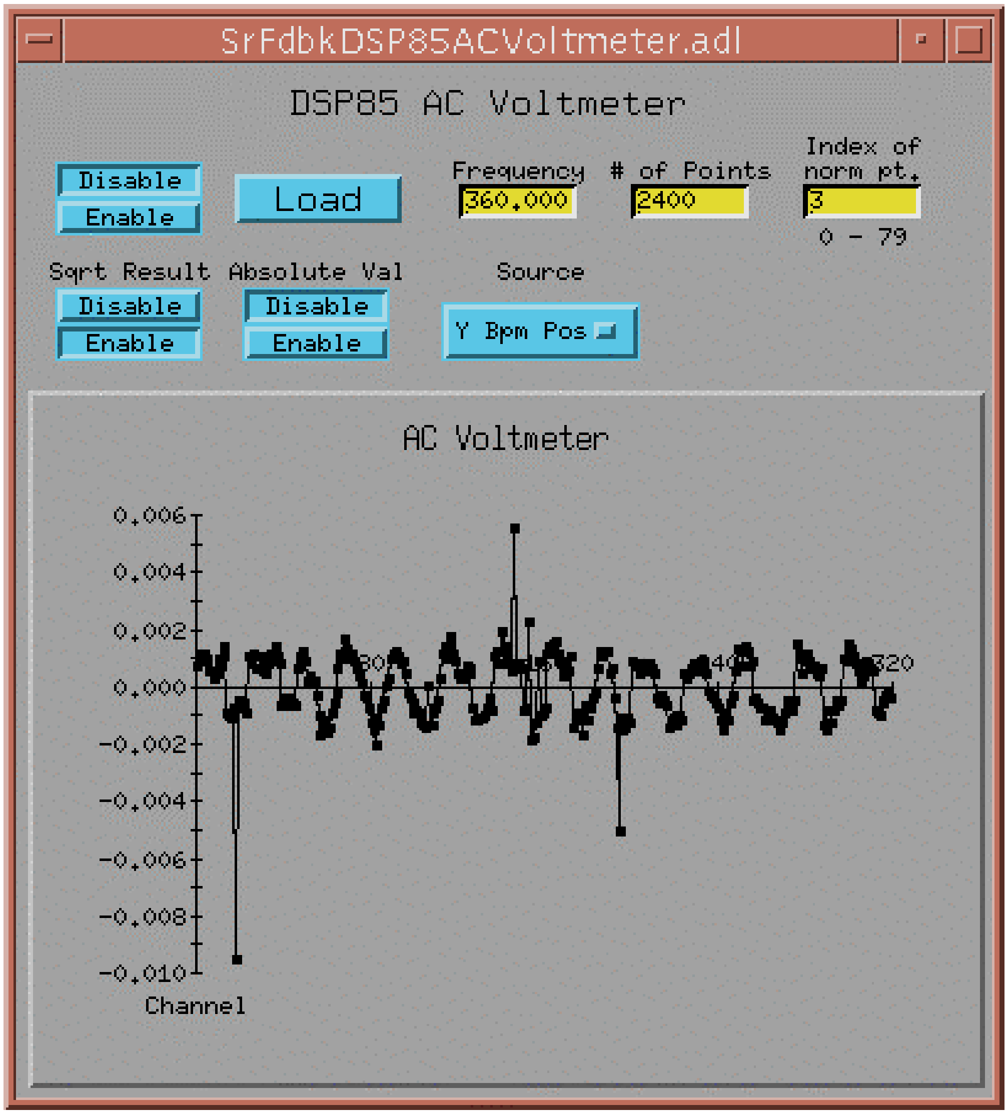
Corrector Error History Buffer

- Maintain a circular buffer of the past 128mS of corrector errors.
- Used to detect and locate sources of unwanted beam motion e.g., following a beam dump.

Waveform Capture using ‘DSPscope’



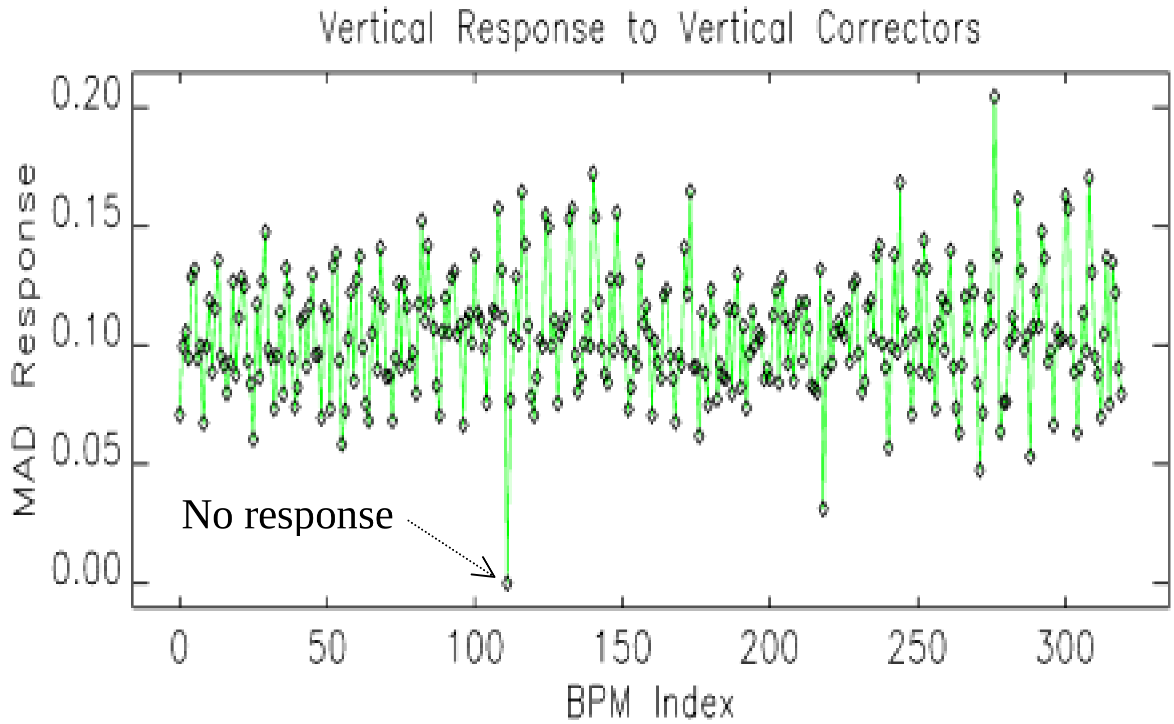
Sliding Fourier Transform
('AC Voltmeter')

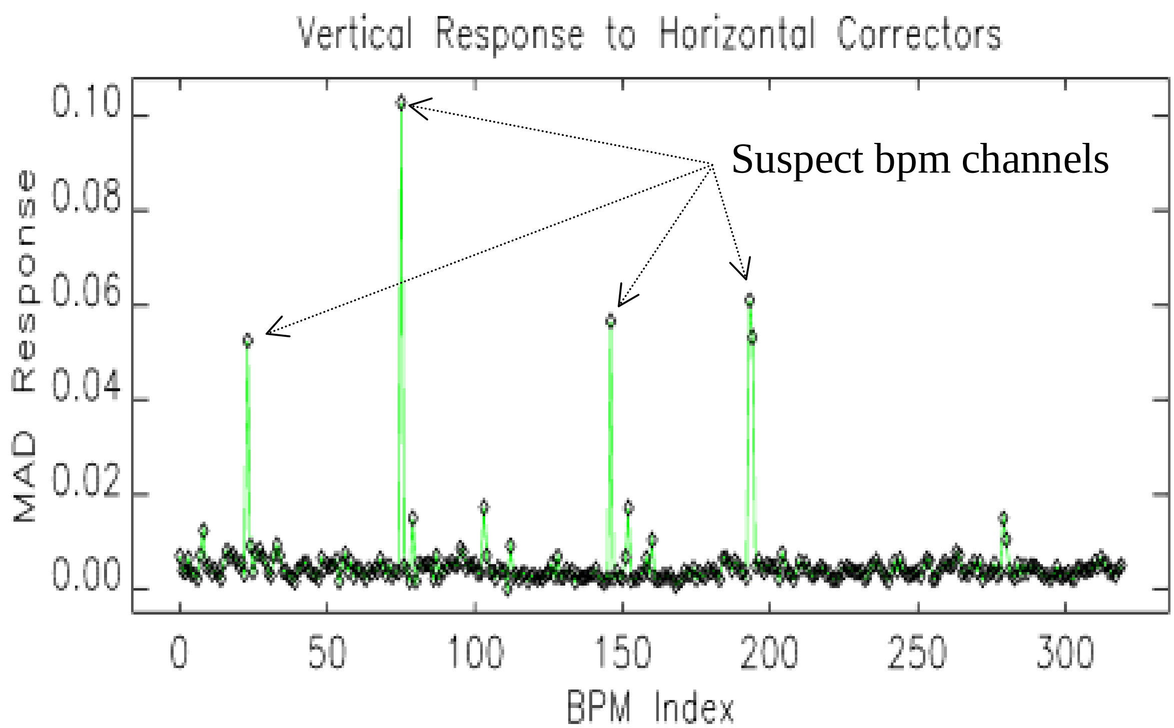


360Hz Fourier Component of 320 bpms

- All 320 bpm channels are simultaneously Fourier analyzed at a chosen frequency.
- One channel is used as a phase reference.
- Used with 'AC-lockin' measurements.

Result from AC-Voltmeter BPM Gain Test

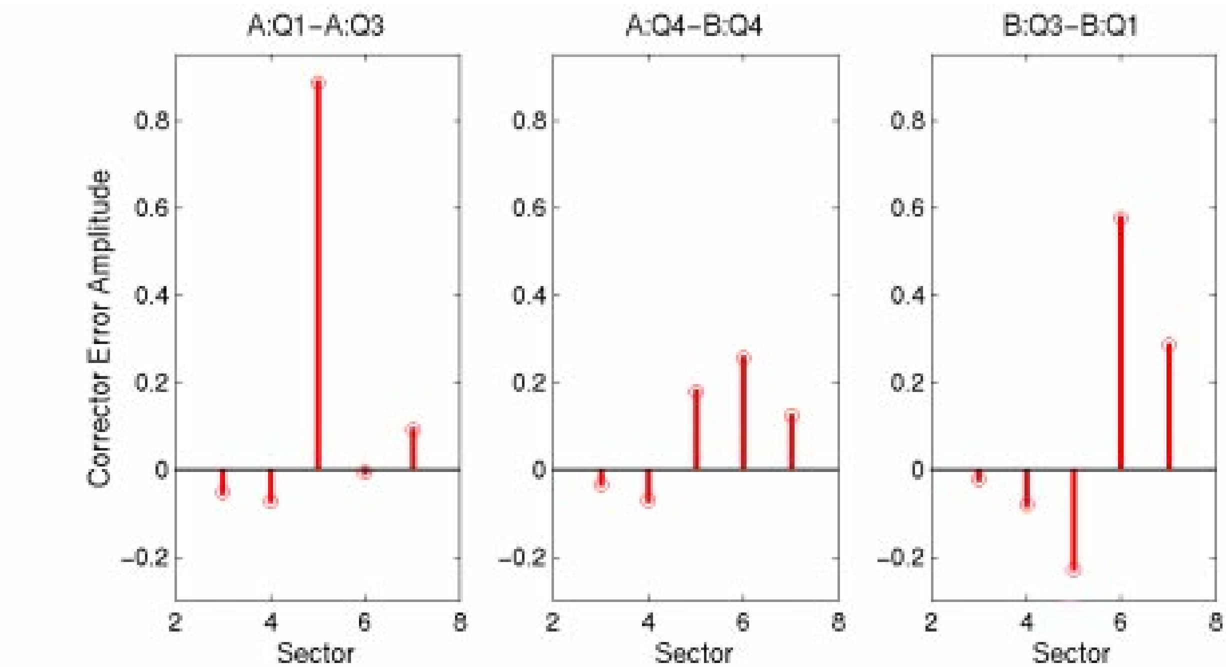




Searching for Sources of Orbit Motion

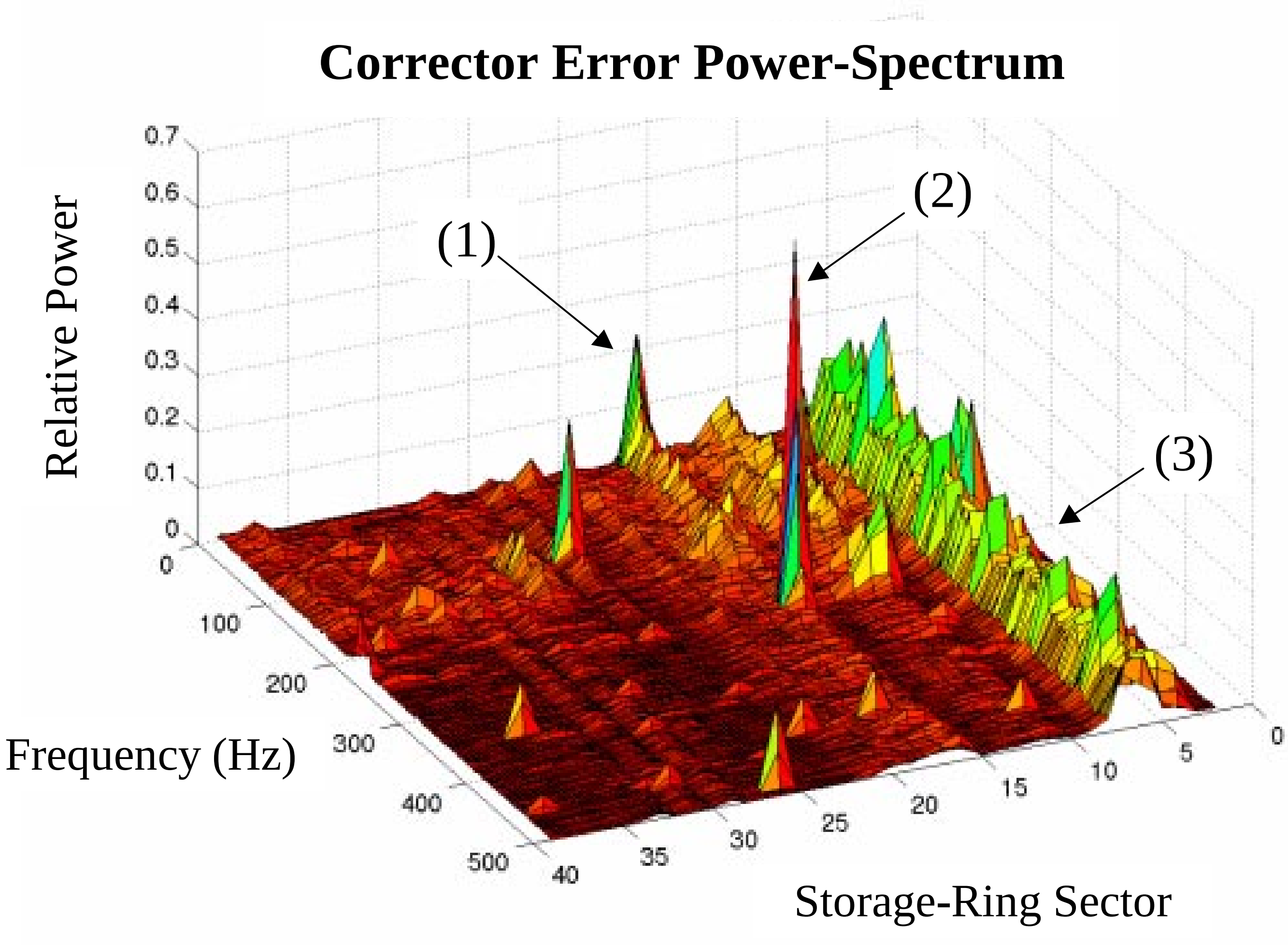
- The location of a source of orbit motion cannot be determined directly from the bpm signals.
- The corrector ‘error’ signal generated during the orbit correction process *can* be used to locate sources.
- All 38 corrector error signals are collected simultaneously at 1kHz.
- Power spectra from the corrector errors provide a roadmap of sources in frequency and space.

Corrector Error Signatures for Different Source Locations



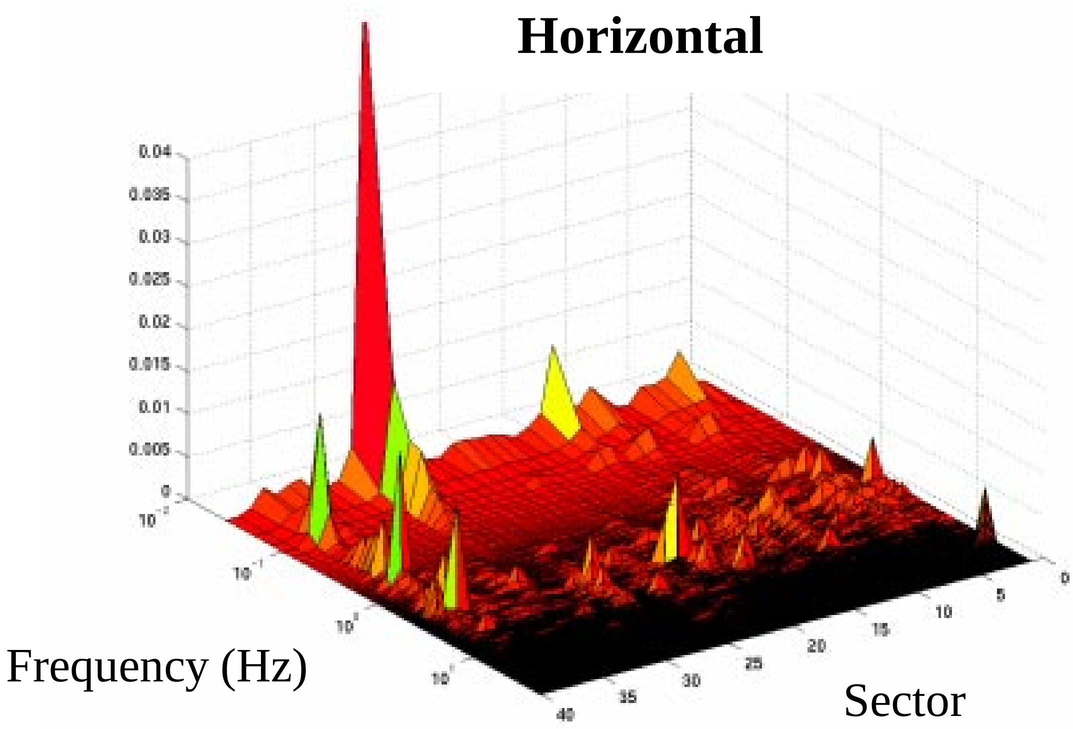
- Ten quadrupoles in sector 6 were excited with AC drive signal (converted to vertical dipole field by asymmetry in vacuum chamber).
- Three distinct corrector error signatures were identified from the ten source locations.
- These same signatures allow real sources of motion to be located to within about one third of a sector (about 9 meters)

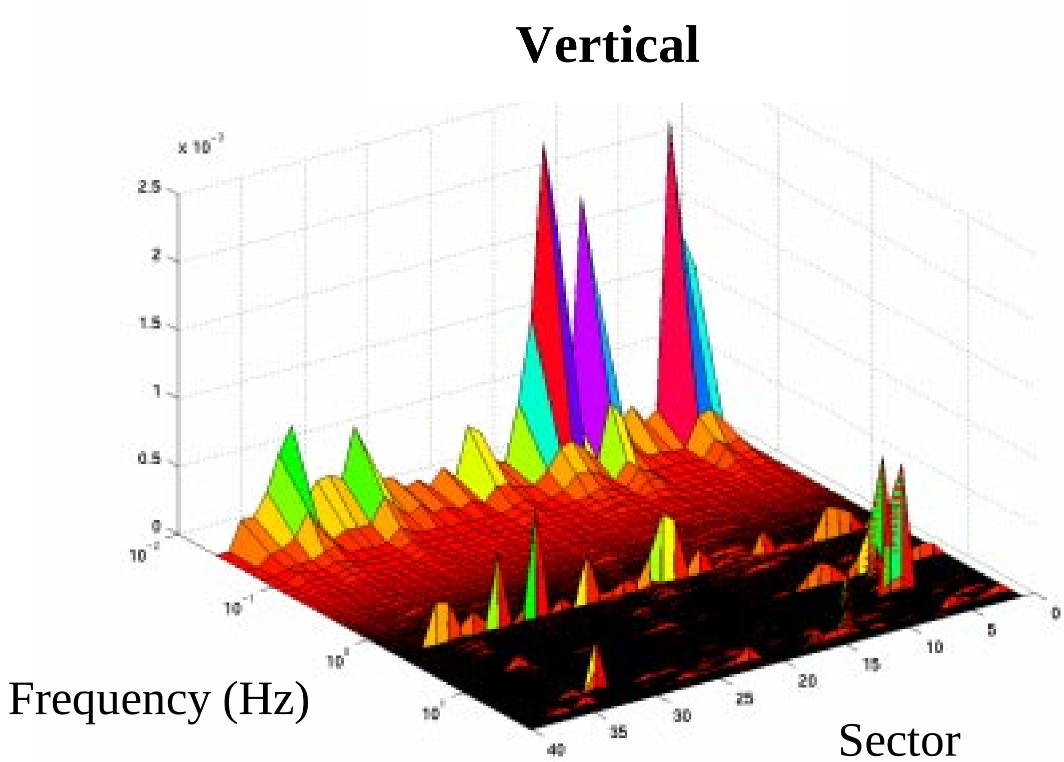
Roadmap of Horizontal Sources (September 1997)



(1) Low frequency random noise from sextupole power supply with poor regulation.
(2) Narrow-band source at 248Hz from oscillating corrector power supply.
(3) Broadband noise caused by bad bpm in sector 6 (not real orbit motion).

Roadmaps of Orbit Motion (March 1998)





Improving the Global Algorithm

Correction Bandwidth

- Correction bandwidth could be improved if the sampling rate were increased.
- But, the sampling rate can only be increased above 2kHz by reducing the number of bpms in the global algorithm (or with faster hardware).
- We can increase the correction bandwidth with no penalty using a higher-order regulator.

Attenuation

- The maximum vertical attenuation would increase from about 15dB to about 25dB by using two correctors per sector instead of one.
- But, correction bandwidth would be reduced because the ‘fast’ correctors must be slowed down to match the equalized ‘slow’ correctors.

Corrector Issues

- It is estimated that quantization errors on 38 correctors produce about 1µm rms of broadband motion.
- A program is underway to increase the resolution beyond the present 16 bits.

Closing Remarks

- Real-time global orbit feedback brings the broadband horizontal orbit stability well within specification.
- Vertical stability below 30Hz is also within specification.
- We have the tools to localize strong sources of orbit motion.
- Local feedback algorithms will be evaluated later this year.
- Long-term goals include reducing vertical rms motion below one micron.